TITLE OF THE INVENTION

PERMANENT MAGNET ROTATING ELECTRIC MACHINE AND

ELECTRICALLY DRIVEN VEHICLE EMPLOYING SAME

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates generally to a permanent magnet rotating electric machine and an electrically driven vehicle employing same.

Description of Related Art

Motors used in electrically driven vehicles, in particular, driving electric cars must ensure a sufficient running distance with a limited battery capacity, so that they are desired to be small, light-weight, and highly efficient.

For a motor to be small and light weight, it is required to be suitable for high speed rotation. In this regard, permanent magnet motors are advantageous over direct-current motors and induction motor.

Permanent magnet rotors are classified into a surface magnet rotor which has permanent magnets positioned along the outer periphery of the rotor and a so-called internal magnet rotor which has a permanent magnet holder within a core made of silicon steel or the like having a higher magnetic permeability than permanent magnets.

1

The surface magnet rotor is advantageous in ease of control, less influences by reactive magnetic flux of a stator winding, low noise, and so on. However, the surface magnet rotor also has several disadvantages such as requirement of reinforced magnets for high speed rotation, a narrow speed control range due to difficulties in field weakening control, a low efficiency in high speed and low load operations, and so on.

The internal magnet rotor, in turn, has advantages such as the capability of high speed rotation by field weakening control using magnetic pole pieces positioned along the outer periphery of magnets, the capability of highly efficient rotation in high speed and low load operations, utilization of reluctance torque, and so on.

Prior art internal magnet rotors are described, for example, in JP-A-5-219669, Fig. 5 of JP-A-7-39091.

Within large-size permanent magnet motors used in electric vehicles and so on, those having an internal permanent magnet rotor employ a distributed winding stator for their stator structure.

However, permanent magnet motors described in the prior art have a disadvantage that pulsating torque based on high frequency components of permanent magnets or auxiliary magnet poles is produced. Also, cogging torque is produced by influence of roughness and fineness of magnetic flux of

2

stator salient poles and roughness and fineness of magnetic

flux of permanent magnets, and smooth rotation of permanent

magnet motors cannot be obtained. Further, since the

distributed winding stator has elongated winding ends, this

causes a limitation to reduction in size and weight of

rotating electric machines employing a distributed winding

stator.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide

a permanent magnet rotating electric machine which has small

pulsating torque and cogging torque, and can be obtained

smooth rotation thereof.

It is another object of the present invention to

provide a permanent magnet rotating electric machine

having shortened winding ends, and having stator

construction being capable to be small, light-weight.

To achieve the above object, according to a first

aspect, the present invention provides a permanent magnet

rotating electric machine comprising a stator having stator

salient poles, three-phases windings wound around said

stator salient poles, a rotor rotatably held inside the said

stator, and permanent magnets inserted into said rotor and

positioned opposite to said stator salient poles, wherein

said three-phase windings are concentratively wound around

3

each of said stator salient poles, said windings of each phase are wound around at more than one stator salient pole, and said windings of each phase have a phase difference of voltage between at least one of the windings and the other.

Preferably, the permanent magnet rotating electric machine satisfies $M:P = 6n:6n\pm2$, where M is the number of the stator salient poles, P is the number of the permanent magnets, and $\underline{n}$ is a positive integer.

Preferably, the permanent magnet rotating electric machine satisfies $M:P = 3n:3n\pm1$, where M is the number of the stator salient poles, P is the number of the permanent magnets of the rotor, and $\underline{n}$ is a positive integer.

Preferably, in the permanent magnet rotating electric machine, the number of poles of the permanent magnets is eight or more.

Preferably, in the permanent magnet rotating electric machine, a magnetic pole piece area of the rotor is projected toward the stator.

Preferably, in the permanent magnet rotating electric machine, a magnetic material having a higher magnetic impermeability than the permanent magnets is disposed between adjacent ones of the permanent magnets.

To achieve the above object, according to a second aspect, the present invention provides a permanent magnet rotating electric machine comprising a stator having stator

salient poles, three-phases windings wound around said stator salient poles, a rotor rotatable held inside the said stator, and permanent magnets inserted into said rotor and positioned opposite to said stator salient poles, wherein said three-phase windings are concentratively wound around each of said stator salient poles.

To achieve the above object, according to an aspect, the present invention provides an electrically driven vehicle comprising a permanent magnet rotating electric machine being coupled to drive wheels comprising a stator having stator salient poles, three-phases windings wound around said stator salient poles, a rotor rotatable held inside the said stator, and permanent magnets inserted into said rotor and positioned opposite to said stator salient poles, and control means for supplying a voltage to said three-phase windings, wherein said three-phase windings are concentratively wound around each of said stator salient poles, said windings of each phase are wound around at more than one stator salient pole, and said control means supplies voltage which has a phase difference between at least one of the windings and the other among each phase of three-phase.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a partial cross-sectional view of a permanent magnet rotating electric machine according to a first embodiment of the present invention, viewed from the front side thereof;

Fig. 2 is a cross-sectional view taken along the section line A-A of Fig. 1, illustrating the permanent magnet rotating electric machine according to the first embodiment of the present invention;

Fig. 3 is a circuit diagram illustrating a control circuit for the permanent magnet rotating electric machine according to the first embodiment of the present invention;

Figs. 4A - 4C are explanatory diagrams illustrating torque generated by the permanent magnet rotating electric machine according to the first embodiment of the present invention;

Figs. 5A - 5C are diagrams for explaining the principles of the permanent magnet rotating electric machine according to the first embodiment of the present invention;

Fig. 6 is a cross-sectional view illustrating a permanent magnet rotating electric machine according to a second embodiment of the present invention;

Fig. 7 is a cross-sectional view illustrating a permanent magnet rotating electric machine according to a third embodiment of the present invention;

Fig. 8 is a cross-sectional view illustrating a

permanent magnet rotating electric machine according to a fourth embodiment of the present invention; and

Fig. 9 is a block diagram illustrating an electric car equipped with a permanent magnet rotating electric machine according to a fifth embodiment of the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Permanent magnet rotating electric machines according to a first embodiment of the present invention will hereinafter be described with reference to Figs. 1 - 5C.

Fig. 1 is a partial cross-sectional view of a permanent magnet rotating electric machine according to a first embodiment of the present invention, viewed from the front side thereof.

Referring specifically to Fig. 1, a stator 20 of a rotating electric machine 10 comprises a stator core 22, multi-phase stator windings 24 wound around the stator core 22, and a housing 26 for securely holding the stator core 22 on the inner peripheral surface thereof. A rotor 30 comprises a rotor core 32, permanent magnets 36 inserted into permanent magnet inserting holes 34 formed in the rotor core 32, and a shaft 38. The shaft 38 is rotatable held by

bearings 42, 44. The bearings 42, 44 are supported by end

brackets 46, 48, respectively, which in turn is secured to

both ends of the housing 26.

A magnetic pole position detector PS for detecting

the position of the permanent magnets 36 of the rotor 30 and

an encoder E for detecting the position of the rotor 30 are

disposed on a side surface of the rotor 30. The operation

of the rotating electric machine 10 is controlled by a

control unit, later described with reference to Fig. 3, in

response to a signal of the magnetic pole position detector

PS and an output signal of the encoder E.

Fig. 2 is a cross-sectional view taken along the

section line A-A of Fig. 1, wherein however, the

illustration of the housing 26 is omitted.

Referring specifically to Fig. 2, the rotating

electric machine 10 comprises the stator 20 and the rotor

30. The rotor 20 comprises the stator core 22 and the

stator windings 24. The stator core 22 comprises an annular

stator yoke 22A and stator salient poles 22B; and the stator

windings 24 are concentratively wound around the stator

salient poles 22B. The respective windings 24 are

configured not to share a magnetic path on gap surfaces. By

employing a stator structure in which the stator windings

are implemented by concentrated windings, the length of end

coil portions can be reduced, and consequently the physical

size of the rotating electric machine can also be reduced.
The end coil portions refer to portions of the stator
windings 24 projecting from the stator core 24 to the left
and right directions in Fig. 1. Since these end coil
portions can be reduced, the entire rotating electric
machine can be reduced in length, thus resulting in a
smaller size of the rotating electric machine.

The U-phase of the stator windings 24 is connected
to U1+, U1-, U2+, U2-, respectively; the V-phase is
connected to V1+, V1-, V2+, V2-, respectively; and W-phase
is connected to W1+, W1-, W2+, W2-, respectively.

The rotor 30 comprises a rotor core 32 formed of a
plurality of laminated plates made of a highly magnetically
permeable material, for example, silicon steel; four
permanent magnets 36 inserted into four permanent magnet
inserting holes 34 formed in the rotor core 32; and a shaft
38. Ten permanent magnets 36 are positioned in the
circumferential direction of the rotor core 32 at equal
intervals such that their polarities are in the opposite
directions from each other.

The rotor core 32 is formed with the permanent
magnet inserting holes 34 and a hole for passing the shaft
38 therethrough, both formed by punch press. Thus, the
rotor 30 is composed of the rotor core 32 made of laminated
silicon steel plates and formed with the punch-pressed

9

permanent magnet inserting holes 34 and hole for passing the shaft 38 therethrough, the permanent magnets 36 inserted into the holes 34, and the shaft 38 extending through the hole.

The rotor core 32 may be divided in the radial direction into an inner yoke area 32A and an outer peripheral area 32B. The outer peripheral area 32B of the rotor core 32 may be further divided in the circumferential direction into an auxiliary magnetic pole area 32B1 and a magnetic pole piece area 32B2. The auxiliary magnetic pole area 32B1, which is an area sandwiched by adjacent permanent magnet inserting holes 34, functions to prohibit magnetic circuits of the magnets from passing therethrough and to allow magnetic flux to be directly generated in the stator by a magnetomotive force of the stator. The magnetic pole piece area 32B2 is an area positioned outside the permanent magnets 36 within the outer peripheral area 32B of the rotor core 32, in which magnetic flux $B\phi$ from the permanent magnets 36 flows through gaps between the permanent magnets 36 and the stator 20 into the stator 20 to form magnetic circuits.

The permanent magnets 36 can be accommodated in the permanent magnet inserting holes 34 which are bordered by the auxiliary magnetic pole area 32B1 in the circumferential

direction and bordered by the magnetic pole piece area 32B2 around the outer periphery, thus providing a motor suitable for high speed rotation.

The concentrated winding stator is generally used in reluctance motors and small brash-less motors. In this case, the reluctance motor includes a rotor only having auxiliary magnetic poles, while the brash-less motor has permanent magnets directly disposed on the outer surface of a rotor. Thus, the reluctance motor generate small torque including large pulsating components.

With the surface magnetic rotor, on the other hand, it is relatively difficult to apply a field weakening control thereto. Accordingly the surface magnetic rotor is likely to cause a loss due to an eddy current generated in surface magnets to reduce the efficiency.

In contrast, a structural combination of a rotor employing internal permanent magnets and a concentrated winding stator allows for utilization of torque generated by flux of the permanent magnets as well as torque generated by reluctance components of the auxiliary magnetic poles, thereby providing a higher efficiency. In addition, since the field weakening can be achieved by the effect of the auxiliary magnetic poles, later described, an operating region can be significantly expanded, particularly, in a high speed region.

Further, since the magnetic pole piece area is made of a magnetic material, pulsating flux from the stator salient poles can be mitigated. Also, since the laminated steel core is employed, the rotating electric machine of the first embodiment is free from eddy current losses.

It is assumed in the example illustrated in Fig. 2 that the rotating electric machine is a three-phase motor which comprises the permanent magnet rotor 36 with the number of poles being ten, and the stator with the number of magnetic poles being twelve. When the number of stator salient poles is represented by M and the number of the poles of the rotor magnets by P, a structure satisfying the following relationship:

$M:P = 6n:6n\pm2$ (where n is a positive integer) can realize reduced torque pulsations and an increased utilization ratio of windings (winding coefficient). It is therefore appreciated that the embodiment illustrated in Fig. 2 can provide a highly efficient, small and light-weight rotating electric machine.

It goes without saying that while the foregoing description has been made in connection with an example of a motor, the first embodiment can be similarly applied to a generator.

Next, a control unit for controlling the permanent magnet rotating electric machine according to the first

12

embodiment will be described with reference to Fig. 3.

Fig. 3 is a circuit diagram of a control circuit for the permanent magnet rotating electric machine according to the first embodiment.

The stator windings 24 of the rotating electric machine 24 are powered from a direct current power source 80 through an invertor 82. A speed control circuit (ASR) 84 calculates a speed difference ωe from a speed instruction ωs and an actual speed ωf derived from positional information θ from the encoder E through an F/V convertor 86, and outputs a torque instruction in accordance with a PI control scheme (P represents a proportional term, and I an integral term) or the like, i.e., a current instruction Is and a rotating angle $\theta 1$ for the rotor 30.

A phase shift circuit 88 shifts the phase of pulses from the encoder E, i.e., the positional information θ from the encoder E in accordance with the rotating angle $\theta 1$ instructed from the speed control circuit (ASR) 84. A sine wave/cosine wave generator 90 generates a sine wave output by shifting the phase of an induced voltage of each of the stator windings 24 (three phases in this embodiment) based on the position detector PS for detecting the positions of the magnetic poles of the permanent magnets of the rotor 30 and the positional information θ on the rotor 30 having its phase shifted by the phase shift circuit 88. The amount of

13

phase shift may be zero.

A two-phase/three-phase convertor circuit 92 outputs current instructions Isa, Isb, Isb to the respective phases in accordance with the current instruction Is from the speed control circuit (ASR) 84 and an output of the sin wave/cosine wave generator 90. The respective phases individually have current control systems (ACR) 94A, 94B, 94C which control respective phase currents by providing the invertor 82 with signals in accordance with the current instructions Isa, Isb, Isc and current detecting signals Ifa, Ifb, Ifc. In this event, a combined current of the respective phase currents is always formed at a position perpendicular to the field flux or at a phase shifted position, so that characteristics equivalent to those of a direct current motor can be achieved without commutator.

When the rotating electric machine of the first embodiment is applied to an electric car, the control unit has a torque control system for directly controlling the torque instead of the speed control circuit 84. In other words, the speed control circuit 84 is replaced with a torque control circuit. The torque control circuit receives torque Ts as an input signal, calculates torque Te from the torque Ts and actual torque Tf detected by a torque detector, and outputs a torque instruction in accordance

14

with a PI control scheme (P represents a proportional term, and I an integral term) or the like, i.e., a current instruction Is and a rotating angle θ1 for the rotor 30.

In a permanent magnet rotating electric machine, since torque is directly proportional to a current, a current control system may be provided instead of the speed control circuit 84.

The connection of the stator windings 24 is made in accordance with a three-phase stator winding scheme. More specifically, U1+, U1-, U2+, U2- are connected in the illustrated order in the U-phase; V1+, V1-, V2+, V2- are connected in the illustrated order in the V-phase; and W1+, W1-, W2+, W2- are connected in the illustrated order in the W-phase. Here, between the windings constituting the respective phases, for example, between U1+ and U2-, and between U1- and U2+ in the U-phase; between V1+ and V2-, and between V1- and V2+ in the V-phase; and between W1+ and W2-, and between W1- and W2+ in the W-phase, there is a phase difference of 30 degrees in electrical angle. Specifically explaining with reference to Fig. 2, for example, an angle θ1 between the stator salient poles U1+ and U2- is 30 degrees, while adjacent permanent magnets 36 of the rotor 30 are angularly spaced by angles θ2. In this way, within the stator salient poles which are wound by the stator windings

15

connected to the same phase, at least one stator salient

pole has a phase shifted with respect to the associated

permanent magnet. Take, as an example, a stator salient

pole around which the winding U1- is wound and a stator

salient pole around which the winding U2+ is wound.

Assuming that U1- is in phase with the permanent magnet 36A,

U1- is shifted from the permanent magnet 36B by an angular

distance of 30 degrees. This contributes to a reduction in

pulsating pulse which may cause a problem in the

concentrated winding stator. The reason for this reduction

will be described later with reference to Fig. 4.

A concentrated winding should be constructed such

that respective windings do not overlap on the gap surface

as illustrated in Fig. 1. This eliminates interference

between the respective windings, and a small, light-weight

and simple rotating electric machine can be realized.

Also, by selecting adjacent windings to be connected

to the same phase as illustrated, the connection is

facilitated. Specifically, in the U-phase, U1+ and U2- are

adjacent, and U1- and U2+ are adjacent. In the V-phase, V1+

and V2- are adjacent, and V1- and V2+ are adjacent.

Similarly, in the W-phase, W1+ and W2- are adjacent, and W1-

and W2+ are adjacent, thus facilitating the connection of

these windings.

Next, the reason for the reduction in torque

pulsation will be explained with reference to Figs. 4A - 4C.

Figs. 4A - 4C show the torque generated by the permanent magnet rotating electric machine according to the first embodiment of the present invention.

Fig. 4A represents torque which is generated when the respective stator windings of U1+, U1-, V1+, V1-, W1+, W1- are applied with a sine wave current based on a signal from the sine wave/cosine wave generator circuit 90 illustrated in Fig. 3. While uniform torque would be generated if no harmonics were included, the inclusion of harmonic components caused by the permanent magnets, harmonic components due to the auxiliary magnetic poles, and so on cause torque pulsation at a period of 60 degrees in electrical angle, as illustrated.

Fig. 4B represents torque which is generated when the respective stator windings of U2+, U2-, V2+, V2-, W2+, W2- are applied with a sine wave current. Since the represented torque includes harmonic components caused by the permanent magnets, harmonic components due to the auxiliary magnetic poles, and so on, as is the case of the torque represented in Fig. 4A, torque pulsations are generated at a period of 60 degrees in electrical angle.

It should be noted herein that since there is a phase difference of 30 degrees in electrical angle between

17

the stator salient poles around which U1+, U1-, V1+, V1-, W1+, W1- of the stator windings 24 are wound and the stator salient poles around which U2+, U2-, V2+, V2-, W2+, W2- of the stator windings 24 are wound, the torque pulsations generated thereby are in opposite phase to each other.

Thus, a combination of torque of Figs. 4A and 4B exhibits reduced pulsations as shown in Fig. 4C.

Referring back to Fig. 2, in the example in which the ratio of the number of permanent magnet M to the number of stator salient poles P is determined to be 10:12, the cogging torque of the permanent magnet rotating electric machine exhibits a number of pulsations per rotation equal to the least common multiple of the number of permanent magnets and the number of stator salient poles , i.e., 60 per rotation in this example. Generally, the cogging torque is smaller as the number of pulsations per rotation is larger.

In a conventionally used motor having a general surface magnet rotor and a concentrated winding stator, the ratio of the number of permanent magnets M to the number of stator salient poles P is typically 2:3. This ratio corresponds to 10:15 when the number of permanent magnets M is changed from two to ten which is the number of permanent magnets M in the example illustrated in Fig. 2. In this case, the number of pulsations per rotation of the cogging

torque is calculated to be 30 which is the least common multiple of 10 and 15. It will be understood from this discussion that the structure of the first embodiment can reduce the cogging torque more than conventional motor of the same type.

In addition, pulsating torque possibly occurring when a current is conducted can be reduced by the principles shown in Fig. 4.

Next, the operation principles of the field weakening control for the permanent magnet rotating electric machine according to the first embodiment will be explained with reference to Figs. 5A - 5C.

Torque T generated by a permanent magnet rotating electric machine is generally expressed by the following equation:

$$T = \{E0 \cdot Iq + (Xq - Xd) \cdot Id \cdot Iq\}/w$$

where E0 is an induced voltage; Xq is reactance on q-axis; Xd is reactance on d-axis; Id is a current on d-axis; Iq is a current on q-axis; and w is an angular rotational speed.

Referring first to Fig. 5A, a permanent magnet 36 is positioned on d-axis, and an auxiliary magnetic pole area 32B1 having a higher magnetic permeability than the permanent magnet 36 is positioned on q-axis. In this arrangement, respective vectors are represented in Fig. 5A. A current Im, which is a combination of the d-axis current

19

Id and the q-axis current Iq, is controlled in the illustrated direction by the current instructions Isa, Isb, Isc generated by the control circuit illustrated in Fig. 3, calculations of output positions of the magnetic pole position detector PS and the encoder E of the rotating electric machine, and so on.

In the foregoing equation, the first term expresses a component of torque generated by the permanent magnet, and the second term expresses a reluctance component generated by the auxiliary magnetic pole area 32B1.

A rotating electric machine for electric car must be controlled so as to maximize the torque/current particularly during a low speed operation. Fig. 5A shows a vector diagram when the rotating electric machine is controlled to generate a maximum torque/current. In this event, the rotating electric machine is controlled to apply an increased magnetomotive force to the auxiliary magnetic pole 32B1, thus taking advantage of the torque generated by the permanent magnet, expressed by the first term, as well as the reluctance torque generated by the auxiliary magnetic pole 32B1, expressed by the second term.

In a high speed region, on the other hand, the torque may be small. Rather, the Id component is increased to cancel the induced voltage E0 of the permanent magnet by Xd·Id in order to weaken the flux of the permanent magnet

20

36, whereby the rotating electric machine can be rotated up to a high speed region. Fig. 5B shows a vector diagram during a high speed operation.

The currents Id, Iq are controlled by the phase shift circuit 88 of the control circuit illustrated in Fig. 3.

Referring next to Fig. 5C, a broken line T2 represents torque generated by a conventional surface magnet rotating electric machine. It can be seen from the broken line T2 that the torque is decreased in a high speed region. A solid line T1, in turn, represents the relationship between the torque and the speed of the permanent magnet rotating electric machine according to the first embodiment, provided by the control described above. Since the current can more easily pass through as compared with the conventional surface magnet rotating electric machine, the permanent magnet rotating electric machine of the first embodiment can be operated in a higher speed region.

According to the first embodiment, since a concentrated winding stator is employed, the end coil portions of the stator can be reduced, so that a smaller rotating electric machine can be provided.

Also, since the stator salient poles, having wound therearound the stator windings connected to the same phase, include at least one salient pole which has a different

phase with respect to the associated permanent magnet, this configuration reduces the pulsating torque which may cause a problem in the concentrated winding stator.

Further, since the permanent magnet rotor is provided with auxiliary magnetic poles, a structure suitable for field weakening control is realized, thereby providing a rotating electric machine appropriate to high speed rotation.

Furthermore, since an auxiliary magnetic pole area made of a magnetic material having a higher magnetic permeability than the permanent magnets is positioned between the permanent magnets, increased torque can be generated.

Moreover, the permanent magnets are surrounded by silicon steel plates, so that a structure suitable for high speed rotation can be provided.

Next, a permanent magnet rotating electric machine according to another embodiment of the present invention will be described with reference to Fig. 6.

Fig. 6 is a cross-sectional view illustrating the permanent magnet rotating electric machine according to a second embodiment of the present invention.

The second embodiment is characterized by a three-phase motor structure which comprises a permanent magnet rotor 36 having ten poles (P=10) and a stator having nine

magnetic poles (M=9). Thus, when the ratio of the number of stator salient poles M to the number of magnetic poles of the stator magnet P (M:P) is 3n:3n±1, reduced torque pulsations and an increased utilization ratio of windings (winding coefficient) can be realized, so that a highly efficient, small, and light-weight rotating electric machine can be provided.

Referring specifically to Fig. 6, the rotating electric machine 10 comprises a stator 20 and a rotor 30. The rotor 20 comprises a stator core 22 and a stator windings 24. The stator core 22 comprises an annular stator yoke 22A and stator salient poles 22B, and the stator windings 24 are concentratively wound around the stator salient poles 22B. The respective windings 24 are configured not to share a magnetic path on gap surfaces. By employing a stator structure in which the stator windings are implemented by concentrated windings, the length of end coil portions can be reduced, and consequently the physical size of the rotating electric machine can also be reduced.

The U-phase of the stator windings 24 is connected to U1+, U1-, U2+, U2-, respectively; the V-phase is connected to V1+, V1-, V2+, V2-, respectively; and W-phase is connected to W1+, W1-, W2+, W2-, respectively.

The rotor 30 comprises a rotor core 34 formed of a plurality of laminated plates made of a highly magnetic

23

permeable material, for example, silicon steel; four

permanent magnets 36 inserted into four permanent magnet

inserting holes 34 formed in the rotor cores 32; and a shaft

38. Ten permanent magnets 36 are positioned in the

circumferential direction of the rotor core 32 at equal

intervals such that their polarities are in the opposite

directions from each other.

The rotor core 32 is formed with the permanent

magnet inserting holes 34 and a hole for passing the shaft

38 therethrough, both formed by punch press. Thus, the

rotor 30 is composed of the rotor core 32 made of laminated

silicon steel plates and formed with the punch-pressed

permanent magnet inserting holes 34 and hole for passing the

shaft 38 therethrough, the permanent magnets 36 inserted

into the holes 34, and the shaft 38 extending through the

hole.

The rotor core 32 may be divided in the radial

direction into an inner yoke area 32A and an outer

peripheral area 32B. The outer peripheral area 32B of the

rotor core 32 may be further divided in the circumferential

direction into an auxiliary magnetic pole area 32B1 and a

magnetic pole piece area 32B2. The auxiliary magnetic pole

area 32B1, which is an area sandwiched by adjacent permanent

magnet inserting holes 34, functions to prohibit magnetic

circuits of the magnets from passing therethrough and to allow magnetic flux to be directly generated in the stator by a magnetomotive force of the stator. The magnetic pole piece area 32B2 is an area positioned outside the permanent magnets 36 within the outer peripheral area 32B of the rotor core 32, in which magnetic flux $B\phi$ from the permanent magnets 36 flows through gaps between the permanent magnets 36 and the stator 20 into the stator 20 to form a magnetic circuit.

The permanent magnets 36 can be accommodated in the permanent magnet inserting holes 34 which are bordered by the auxiliary magnetic pole area 32B1 in the circumferential direction and bordered by the magnetic pole piece area 32B2 around the outer periphery, thus providing a rotating electric machine suitable for high speed rotation.

Further, since the magnetic pole piece area is made of a magnetic material, pulsating flux from the stator salient poles can be mitigated. Also, since the laminated steel core is employed, the rotating electric machine of the second embodiment is free from eddy current losses.

It is assumed in the example illustrated in Fig. 6 that the rotating electric machine is a three-phase motor which comprises the permanent magnet rotor 36 with the number of poles P being ten, and the stator with the number of magnetic poles being nine. When the number of stator

25

salient poles is represented by M and the number of the

poles of the rotor magnets by P, a structure satisfying the

following relationship:

M:P = 3n:3n±1 (where n is a positive integer)

can realize reduced torque pulsations and an increased

utilization ratio of windings (winding coefficient), so that

a highly efficient, a small and light-weight rotating

electric machine can be provided.

The connection of the stator windings 24 is made in

accordance with a three-phase stator winding scheme. More

specifically, U1+, U1-, U2+ are connected in the illustrated

order in the U-phase; V1+, V1-, V2+ are connected in the

illustrated order in the V-phase; and W1+, W1-, W2+ are

connected in the illustrated order in the W-phase. Here,

the windings constituting the respective phases, for

example, U1+ and U1-, and U1- and U2+ in the U-phase; V1+

and V1-, V1- and V2+ in the V-phase; and W1+ and W1-, W1-

and W2+ in the W-phase, have a phase difference of 20

degrees in electrical angle. In this way, the stator

salient poles having wound therearound the stator windings

connected to the same phase, increase at least one stator

salient pole which has a different phase with respect to the

associated permanent magnet. Take, as an example, a stator

salient pole having wound therearound the winding U1- and a

stator salient pole having wound therearound the winding

26

U2+. Assuming that U1- is in phase with the permanent

magnet 36A, U1- is shifted from the permanent magnet 36B by

an angular distance of 30 degrees. This contributes to a

reduction in pulsating torque which may cause a problem in

the concentrated winding stator.

An electrical angle between adjacent stator salient

poles 22B is calculated to be 200 degrees (180x(10/9)=200),

and 20 degrees when taking into account the phase

difference. The cogging torque of the permanent magnet

rotating electric machine exhibits a number of pulsations

per rotation equal to the least common multiple of the

number of permanent magnets and the number of stator salient

poles , i.e., 90 per rotation in this example.

In the example illustrated in Fig. 2 in which the

ratio of the number of permanent magnets M to the number of

stator salient poles P is 10:12, the cogging torque of the

permanent magnet rotating electric machine exhibits

pulsations of 60 per rotation. It is understood from this

discussion that the second embodiment can further reduce the

cogging torque.

It goes without saying that while the foregoing

description has been made in connection with an example of a

motor, the second embodiment can be similarly applied to a

generator.

According to the second embodiment, since a

27

concentrated winding stator is employed, the end coil portions of the stator can be reduced in length, so that a smaller rotating electric machine can be provided.

Also, since the stator salient poles, having wound therearound stator windings connected to the same phase, include at least one salient pole which has a different phase with respect to the associated permanent magnet, this configuration reduces the pulsating torque which may cause a problem in the concentrated winding stator.

In addition, the cogging torque can be further reduced.

Further, since the permanent magnet rotor is provided with auxiliary magnetic poles, a structure suitable for field weakening control is realized, thereby providing a rotating electric machine appropriate to high speed rotations.

Furthermore, since an auxiliary magnetic pole area made of a magnetic material having a higher magnetic permeability than the permanent magnets is positioned between the permanent magnets, increased torque can be generated.

Moreover, the permanent magnets are surrounded by silicon steel plates, so that a rotating electric machine suitable for high speed rotations can be provided.

Next, a permanent magnet rotating electric machine

28

according to a third embodiment of the present invention will be described with reference to Fig. 7.

Fig. 7 is a cross-sectional view illustrating the permanent magnet rotating electric machine according to the third embodiment of the present invention.

The third embodiment is characterized by a three-phase motor structure which comprises a permanent magnet rotor 36 having twelve poles (P=12) and a stator having eight magnetic poles (M=8). Since this structure can increase the utilization ratio of windings (winding coefficient), a highly efficient, small, and light-weight rotating electric machine can be provided.

Referring specifically to Fig. 7, the rotating electric machine 10 comprises a stator 20 and a rotor 30. The rotor 20 comprises a stator core 22 and a stator windings 24. The stator core 22 comprises an annular stator yoke 22A and stator salient poles 22B, and the stator windings 24 are concentratively wound around the stator salient poles 22B. The respective windings 24 are configured not to share a magnetic path on gap surfaces. By employing a stator structure in which the stator windings are implemented by concentrated windings, end coil portions can be reduced in length, and consequently the physical size of the rotating electric machine can also be reduced.

The U-phase of the stator windings 24 is connected

29

to U1, U2, U3, U4, respectively; the V-phase is connected to V1, V2, V3, V4, respectively; and W-phase is connected to W1, W2, W3, W4, respectively.

The rotor 30 comprises a rotor core 34 formed of a plurality of laminated plates made of a highly magnetic permeable material, for example, silicon steel; four permanent magnets 36 inserted into four permanent magnet inserting holes 34 formed in the rotor cores 32; and a shaft 38. Ten permanent magnets 36 are positioned in the circumferential direction of the rotor core 32 at equal intervals such that their polarities are in the opposite directions from each other.

The rotor core 32 is formed with the permanent magnet inserting holes 34 and a hole for passing the shaft 38 therethrough, both formed by punch press. Thus, the rotor 30 is composed of the rotor core 32 made of laminated silicon steel plates and formed with the punch-pressed permanent magnet inserting holes 34 and hole for passing the shaft 38 therethrough, the permanent magnets 36 inserted into the holes 34, and the shaft 38 extending through the hole.

The rotor core 32 may be divided in the radial direction into an inner yoke area 32A and an outer peripheral area 32B. The outer peripheral area 32B of the rotor core 32 may be further divided in the circumferential

direction into an auxiliary magnetic pole area 32B1 and a magnetic pole piece area 32B2. The auxiliary magnetic pole area 32B1, which is an area sandwiched by adjacent permanent magnet inserting holes 34, functions to prohibit magnetic circuits of the magnets from passing therethrough and to allow magnetic flux to be directly generated in the stator by a magnetomotive force of the stator. The magnetic pole piece area 32B2 is an area positioned outside the permanent magnets 36 within the outer peripheral area 32B of the rotor core 32, in which magnetic flux $B\phi$ from the permanent magnets 36 flows through gaps between the permanent magnets 36 and the stator 20 into the stator 20 to form a magnetic circuit.

The permanent magnets 36 can be accommodated in the permanent magnet inserting holes 34 which are bordered by the auxiliary magnetic pole area 32B1 in the circumferential direction and bordered by the magnetic pole piece area 32B2 around the outer periphery, thus providing a rotating electric machine suitable for high speed rotation.

Further, since the magnetic pole piece area is made of a magnetic material, pulsating flux from the stator salient poles can be mitigated. Also, since the laminated steel core is employed, the rotating electric machine of the second embodiment is free from eddy current losses.

It is assumed in the example illustrated in Fig. 7

31

that the rotating electric machine is a three-phase motor

which comprises the permanent magnet rotor 36 with the

number of poles P being twelve, and the stator with the

number of magnetic poles being eight. Since such a

structure achieves an increased utilization ratio of the

windings (winding coefficient), a highly efficient, small

and light-weight rotating electric machine can be provided.

The connection of the stator windings 24 is made in

accordance with a three-phase stator winding scheme. More

specifically, U1, U2, U3, U4 are connected in the

illustrated order in the U-phase; V1, V2, V3, V4 are

connected in the illustrated order in the V-phase; and W1,

W2, W3, W4 are connected in the illustrated order in the W-

phase. The windings forming parts of the U-phase, V-phase,

W-phase have a phase difference of 60 degrees between each

other.

In the third embodiment, the stator salient poles

having wound therearound the stator windings connected to

the same phase are in phase with the associated permanent

magnets, so that a reduction in torque pulsation is not

expected. However, since the salient poles in phase with

the permanent magnets are positioned in a symmetric

configuration, a well balanced structure can be provided.

More specifically explaining with reference to the U-phase,

the respective salient poles U1, U2, U3, U4 are positioned symmetrically about the shaft 38.

It goes without saying that while the foregoing description has been made in connection with an example of a motor, the third embodiment can be similarly applied to a generator.

According to the third embodiment, since a concentrated winding stator is employed, the end coil portions of the stator can be reduced in length, so that a smaller rotating electric machine can be provided.

Also, since the permanent magnet rotor is provided with auxiliary magnetic poles, a structure suitable for field weakening control is realized, thereby providing a rotating electric machine appropriate to high speed rotations.

Further, since an auxiliary magnetic pole area made of a magnetic material having a higher magnetic permeability than the permanent magnets is positioned between the permanent magnets, increased torque can be generated.

Moreover, the permanent magnets are surrounded by silicon steel plates, so that a rotating electric machine suitable for high speed rotations can be provided.

Next, a permanent magnet rotating electric machine according to a fourth embodiment of the present invention will be described with reference to Fig. 8.

Fig. 8 is a cross-sectional view illustrating the permanent magnet rotating electric machine according to the fourth embodiment of the present invention.

The fourth embodiment is characterized by a three-phase motor structure which comprises a permanent magnet rotor 36 having twelve poles (P=12) and a stator having eight magnetic poles (M=8). Since this structure can increase the utilization ratio of windings (winding coefficient), a highly efficient, small, and light-weight rotating electric machine can be provided.

In addition, a magnetic pole piece area of the rotor is projected toward the magnetic poles of the stator, such that a sinusoidal magnetic flux distribution is produced.

Referring specifically to Fig. 8, the rotating electric machine 10 comprises a stator 20 and a rotor 30. The rotor 20 comprises a stator core 22 and a stator windings 24. The stator core 22 comprises an annular stator yoke 22A and stator salient poles 22B, and the stator windings 24 are concentratively wound around the stator salient poles 22B. The respective windings 24 are configured not to share a magnetic path on gap surfaces. By employing a stator structure in which the stator windings are implemented by concentrated windings, end coil portions can be reduced in length, and consequently the physical size of the rotating electric machine can also be reduced.

The U-phase of the stator windings 24 is connected to U1, U2, U3, U4, respectively; the V-phase is connected to V1, V2, V3, V4, respectively; and W-phase is connected to W1, W2, W3, W4, respectively.

The rotor 30 comprises a rotor core 34 formed of a plurality of laminated plates made of a highly magnetic permeable material, for example, silicon steel; four permanent magnets 36 inserted into four permanent magnet inserting holes 34 formed in the rotor cores 32; and a shaft 38. Ten permanent magnets 36 are positioned in the circumferential direction of the rotor core 32 at equal intervals such that their polarities are in the opposite directions from each other.

The rotor core 32 is formed with the permanent magnet inserting holes 34 and a hole for passing the shaft 38 therethrough, both formed by punch press. Thus, the rotor 30 is composed of the rotor core 32 made of laminated silicon steel plates and formed with the punch-pressed permanent magnet inserting holes 34 and hole for passing the shaft 38 therethrough, the permanent magnets 36 inserted into the holes 34, and the shaft 38 extending through the hole.

The rotor core 32 may be divided in the radial direction into an inner yoke area 32A and an outer peripheral area 32B. The outer peripheral area 32B of the

rotor core 32 may be further divided in the circumferential direction into an auxiliary magnetic pole area 32B1 and a magnetic pole piece area 32B2. The auxiliary magnetic pole area 32B1, which is an area sandwiched by adjacent permanent magnet inserting holes 34, functions to prohibit magnetic circuits of the magnets from passing therethrough and to allow magnetic flux to be directly generated in the stator by a magnetomotive force of the stator. In the fourth embodiment, the magnetic pole piece area of the rotor is projected toward the stator magnetic poles 22B to shape a sinusoidal magnetic flux distribution.

The permanent magnets 36 can be accommodated in the permanent magnet inserting holes 34 which are bordered by the auxiliary magnetic pole area 32B1 in the circumferential direction and bordered by the magnetic pole piece area 32B2 around the outer periphery, thus providing a rotating electric machine suitable for high speed rotation.

Further, since the magnetic pole piece area is made of a magnetic material, pulsating flux from the stator salient poles can be mitigated. Also, since the laminated steel core is employed, the rotating electric machine of the second embodiment is free from eddy current losses.

It is assumed in the example illustrated in Fig. 8 that the rotating electric machine is a three-phase motor which comprises the permanent magnet rotor 36 with the

36

number of poles P being twelve, and the stator with the number of magnetic poles being eight. Since such a structure achieves an increased utilization ratio of the windings (winding coefficient), a highly efficient, small and light-weight rotating electric machine can be provided.

The connection of the stator windings 24 is made in accordance with a three-phase stator winding scheme. More specifically, U1, U2, U3, U4 are connected in the illustrated order in the U-phase; V1, V2, V3, V4 are connected in the illustrated order in the V-phase; and W1, W2, W3, W4 are connected in the illustrated order in the W-phase. The windings forming parts of the U-phase, V-phase, W-phase have a phase difference of 60 degrees between each other.

In the fourth embodiment, the stator salient poles, having wound therearound the stator windings connected to the same phase, are in phase with the associated permanent magnets, so that a reduction in torque pulsation is not expected. However, since the salient poles in phase with the permanent magnets are positioned in a symmetric configuration, a well balanced structure can be provided. More specifically explaining with reference to the U-phase, the respective salient poles U1, U2, U3, U4 are positioned symmetrically about the shaft 38.

It goes without saying that while the foregoing

37

description has been made in connection with an example of a motor, the fourth embodiment can be similarly applied to a generator.

According to the fourth embodiment, since a concentrated winding stator is employed, the end coil portions of the stator can be reduced in length, so that a smaller rotating electric machine can be provided.

Also, since the permanent magnet rotor is employed, a structure suitable for field weakening control is realized, thereby providing a rotating electric machine appropriate to high speed rotations.

Moreover, the permanent magnets are surrounded by silicon steel plates, so that a rotating electric machine suitable for high speed rotations can be provided.

While the foregoing respective embodiments have been described in connection with a control system which controls a sinusoidal current with respect to the position of the rotor, it goes without saying that the present invention may also be applied to a 120 degree conductive brash-less motor scheme which does not perform a current control.

Also, while the foregoing description has been made with reference to an internal rotation type motor, the present invention may also be applied to external rotation type motors, generators, and linear motors.

Next, an electric car employing a permanent magnet

rotating electric machine according to a fifth embodiment
will be described with reference to Fig. 9.

Fig. 9 is a block diagram illustrating the
configuration of an electric car which is equipped with a
permanent magnet rotating electric machine according to the
fifth embodiment of the present invention.

A body 100 of the electric car is supported by four
wheels 110, 112, 114, 116. Since this electric car is a
front-wheel driven type, a permanent magnet rotating
electric machine 120 is directly coupled to a front wheel
shaft 154. The permanent magnet rotating electric machine
120 has a structure as illustrated in Fig. 2, 6, 7 or 8. A
control unit 130 is provided for controlling driving torque
of the permanent magnet rotating electric machine 120. A
battery 140 is provided as a power source for the control
unit 130. Electric power from the battery 140 is supplied
to the permanent magnet rotating electric machine 120
through the control unit 130, thereby driving the permanent
magnet rotating electric machine 120 to rotate the wheels
110, 114. The rotation of a steering wheel 150 is
transmitted to the two wheels 110, 114 through a
transmission mechanism including a steering ring gear 152, a
tie rod, a knuckle arm, and so on to change the angle of the
wheels 110, 114.

It should be noted that while in the foregoing

embodiment, the permanent magnet rotating electric machine

has been described to be used for driving wheels of an

electric car, the permanent magnet rotating electric machine

may also be used for driving wheels of an electric

locomotive or the like.

According to the fifth embodiment, when the

permanent magnet rotating electric machine is applied to an

electrically driven vehicle, particular to an electric car,

a small, light-weight, and highly efficient permanent magnet

rotating electric machine can be equipped in the vehicle,

thus making it possible to provide an electric car which can

run a longer distance with the amount of electric power

accumulated in one recharging operation.